GA–C25590

INJECT 2 MW OF NEUTRAL BEAM POWER IN THE COUNTER DIRECTION ON DIII-D AND BEGIN PHYSICS EXPERIMENTS

Milestone 161

by
K.H. Burrell for the
DIII-D Research Team

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GENERAL ATOMICS

MILESTONE 161

Inject 2 MW of Neutral Beam Power in the Counter Direction on DIII-D and Begin Physics Experiments

DESCRIPTION OF DELIVERABLE

Q1 Install new beamline port needed to interface the rotated beamline with the vessel for counter injection.

Q2 Complete reinstallation of modified beamline hardware (beamline support stands and spools).

Q3 Complete beamline hardware system checkout. Reinstall ion sources and prepare the modified beam system for operation.

Q4 Inject 2 MW of deuterium neutrals into plasma from the modified beamline and begin physics experiments.

DESCRIPTION OF COMPLETION

Final Report

I. INTRODUCTION

This is the final milestone report, which is the definition of completion for Milestone 161: Inject 2 MW of neutral beam power in the counter direction on DIII-D and begin physics experiments.

This milestone was broken down into four parts, to be accomplished in the four quarters of fiscal year 2006. These parts are

First quarter: Install new beamline port needed to interface the rotated beamline with the vessel for counter injection.

Second quarter: Complete reinstallation of modified beamline hardware (beamline support stands and spools).

Third quarter: Complete beamline hardware system checkout. Reinstall ion sources and prepare the modified beam system for operation.

Fourth quarter: Inject 2 MW of deuterium neutrals into plasma from the modified beamline and begin physics experiments.

This report briefly covers the first three quarterly milestones, which are hardware construction milestones, and then goes on to document some of the initial physics experiments which were performed using the new neutral beam capability. Routine operation of the counter beams at total powers above 5 MW has been available for physics experiments during the 2006 campaign.

II. MOTIVATION

Creating the capability for simultaneous co- plus counter-neutral beam injection in DIII-D enables a large number of key physics experiments. These experiments support essentially all of the goals of the DIII-D program. They include

1. Improve current profile control in AT discharges,
2. Allow study of RWM and NTM stabilization as a function of plasma rotation rate,
3. Add new tool for Alfvén eigenmode experiments,
4. Allow operation at very high bootstrap current fraction by reducing neutral beam current drive,
5. Improve measurement of current density $J(r)$ with MSE system,
6. Expand QH-mode and QDB operating space,
7. Improve understanding of physics of rotation,
8. Separate the effect of rotation-induced $E \times B$ shear and Shafranov shift (α stabilization) in core barrier formation,
9. Transport barrier control through direct alteration of $E \times B$ shear.

III. SUMMARY OF CONSTRUCTION MILESTONES

In order to satisfy the overall level 1 milestone, a substantial amount of hardware reconstruction was required. The existing 210 deg beamline on DIII-D had to be removed, the support structure and vacuum vessel interface rebuilt and then the whole system reinstalled and returned to operation. The first three quarterly, hardware milestones associated with this work were all successfully completed on or ahead of schedule.

A. First quarter milestone

The new beamline port was installed on December 20, 2005, somewhat ahead of the scheduled date of December 31, 2005. Prior to the first quarter of FY06, the neutral beamline at 210 deg and its control electronics, vacuum system, cryo system, high voltage transmission line and magnet power supplies were removed from the DIII-D machine hall and moved to the high bay area. In addition, several diagnostics and part of the fast wave system had to be removed.

While the beamline components were located in the high bay area, repairs were made to the internal components of the 210 beamline, and the neutral beam stand was modified. The repairs included repair of a water leak in the cooling line to the calorimeter and replacement of the magnet pole shield. A new driftduct weldment (port adapter) was manufactured. Copper was shaved off the toroidal field coil turns next to the 210R0 port in order to make room for the new drift duct weldment.

After the modification of the beamline stand it was reinstalled in the machine hall. The drift duct was mounted to the spool piece closest to the vessel and test fitted to the port. It was then removed again and moved to the high bay, where holes were drilled for the drift duct collimator. The rebuilt B-coil feed leads were then installed before the drift duct was moved back to the machine hall and welded to the 210 port.

B. Second quarter milestone

The second quarter milestone was completed on January 9, 2006, well ahead of the scheduled date of March 31, 2006.

Prior to meeting the first quarter milestone, installation of spools #2 and #3 on the redirected beam stand was accelerated because of delays with the toroidal bus feed. The ion source-housing stand was installed in September 2005. Spool # 1 was moved into the machine hall and placed on the beam stand at the end of December 2005. The beamline endplate, the ion source isolation valves and ion source housing were installed in early January 2006. Alignment of the beam path was documented shortly after that.

C. Third quarter milestone

The third quarter milestone was completed on May 5, 2006, somewhat ahead of the scheduled date of June 30, 2006

After the 210 deg neutral beam components were reinstalled in the DIII-D machine hall in their new, rotated position, considerable work was required to prepare the neutral beam for operations. In particular, the many control and power cables required to operate the beam were reconnected, cooling water circuits were reconnected and tested, and all the systems and associated interlocks were tested including the pole shield thermocouple array and the bending magnet power supplies. The two ion sources, which had been kept under vacuum during the whole shutdown period, were quickly reconditioned up to their full operating voltages and power levels. On May 5, 2006 the first 20-ms-long beam blips were fired into the DIII-D vessel demonstrating the rotated beamline with both ion sources was ready for operation.

IV. INITIAL OPERATION AND OPERATION WITH THE PLASMA CONTROL SYSTEM

On May 22, 2006, over 5 MW of power was injected from the 210 deg beamline into a tokamak plasma. This is the standard level of operation for the two ion sources in the 210 beamline and well exceeds the minimum, 2 MW level called for in the level 1 milestone. Since that time, the co- plus counter-neutral beam capability has been in routine use for DIII-D experiments. An illustration of a shot with both 210 ion sources injecting is given in Fig. 1. As can be seen there, substituting two counter beams for two co-injected beams produces a substantial change in the plasma rotation. The rotation change shown in Fig. 1 demonstrates the control of plasma rotation which was one of the main goals of the work covered in this milestone.

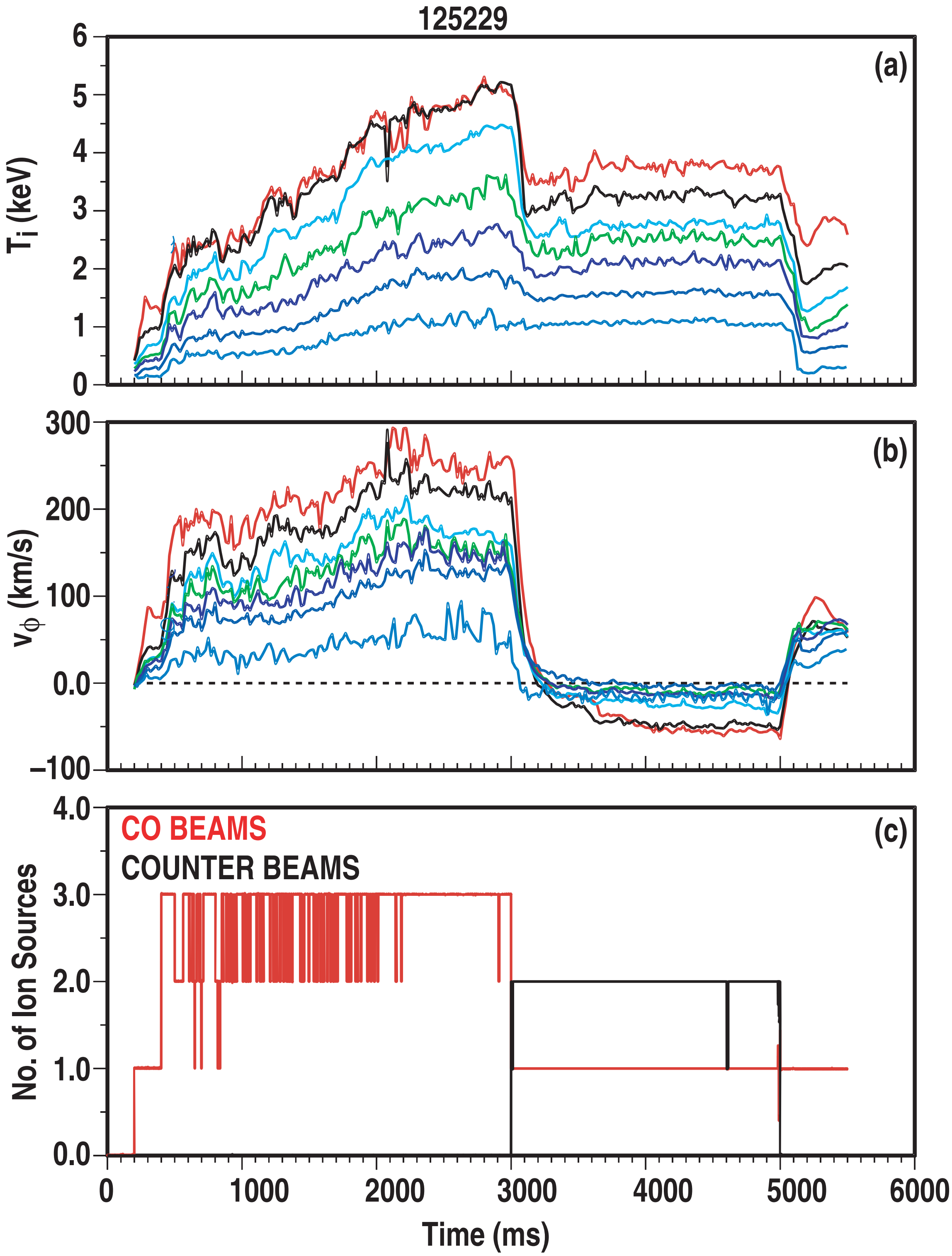

Fig. 1. Plot of ion temperature (a) and toroidal rotation speed (b) as at various radii a function of time for a shot in which the mix of co- and counter-neutral beams (c) is changed at 3000 ms, resulting in a reversal of the toroidal rotation speed and a decrease in the ion temperature.

Using the capability for simultaneous co- plus counter-injection, we can now separately control the plasma rotation and the total plasma energy. The rotation depends on the net torque, with the counter-beams providing counter (negative) torque, while the total energy depends on the total heating power. As is illustrated in Fig. 2, by using the digital plasma control system (PCS) on DIII-D, coupled with real-time measurements of plasma rotation and energy, we are able to simultaneously feedback control both the rotation and the stored energy. The stored energy determination from real-time EFIT equilibrium analysis has been routinely available for several years. In addition to the counter-neutral beam capability, achieving feedback control of rotation using the PCS required coupling the charge exchange spectroscopy (CER) measurements to the PCS and implementing real-time analysis of the CER spectra to extract the plasma rotation from the Doppler shift of the spectral lines. At present, we have an eight point radial profile of rotation (and ion temperature) which is available every 6 ms. This same capability allows feedback control of the ion temperature if desired.

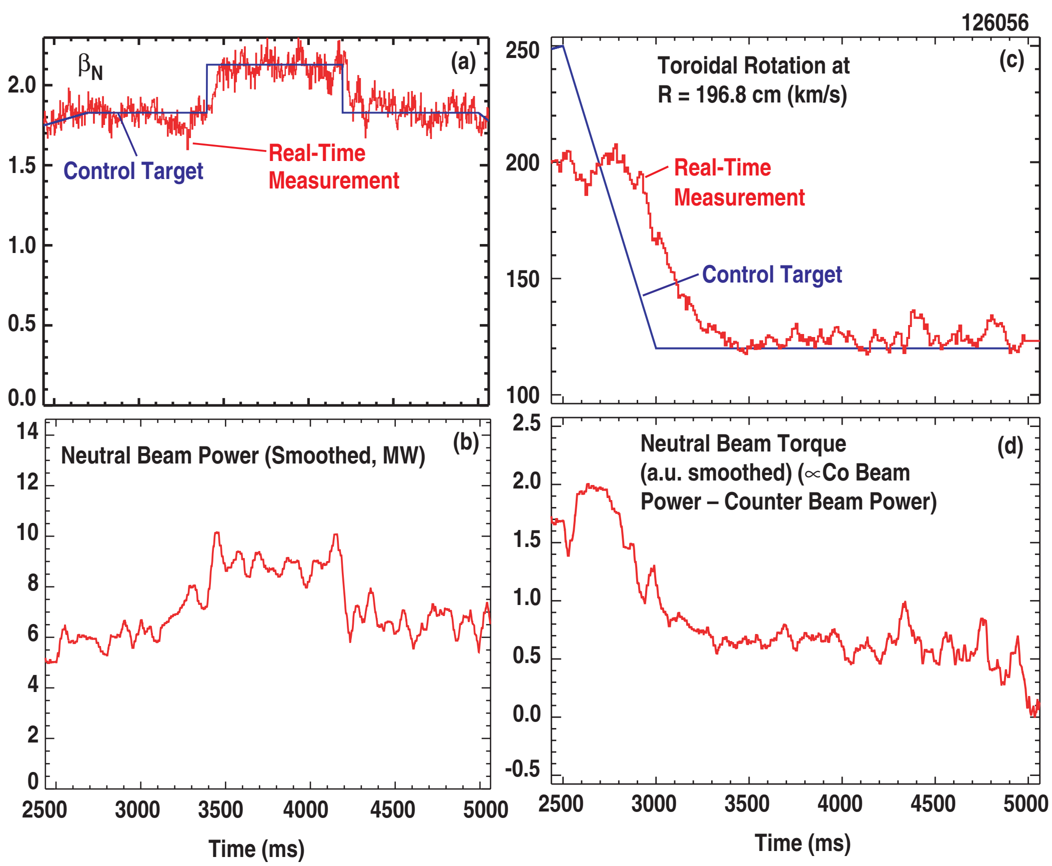

Fig. 2. Example of simultaneous control of normalized beta, β_N (a), and toroidal rotation (c) using simultaneous co- plus counter-neutral beam injection controlled by the DIII-D PCS. Note that the rotation does not change when β_N is varied by changing its control target during the 3500 to 4000 ms time interval and that β_N does not vary as the toroidal rotation is decreasing during the 3000 to 3500 ms interval.

V. EXPERIMENTS ENABLED BY REVERSING THE 210 BEAMLINE

The co- plus counter-neutral beam injection capability has been used extensively in a number of experiments during the 12 operating weeks of the 2006 run campaign on DIII-D (June-September 2006). To illustrate the work that has been done, this section briefly discusses seven different areas where the co- plus counter-injection capability was essential for the experiment. Many of these experiments will be discussed in more detail at the upcoming IAEA and APS/DPP meetings. The associated IAEA papers are attached to this milestone report.

A. Charge exchange spectroscopy using co- plus counter-beams

Charge exchange spectroscopy (CER) is the standard technique for measuring the ion rotation and ion temperature in neutral-beam-heated tokamak plasmas. As is well known [1], the energy dependence of the charge exchange cross section can produce apparent velocity shifts in the spectra which can lead to a systematic error in the inferred toroidal rotation speed. This apparent velocity shift is essentially a vector along the direction of the neutral beam [2]. Accordingly, it gives a different contribution to the net inferred speed depending on the direction of the neutral beam relative to the actual plasma toroidal rotation. Previously, this effect of the energy dependent cross section has been calculated from the atomic physics data. As part of the improvements to DIII-D in 2005 and 2006, we equipped the machine with CER views of the 210, counter beam to supplement the previously existing views of the co-injected beams. Using both sets of views, we can directly determine the effect of the energy dependent cross section and check the results of the atomic physics measurement. One such check is shown in Fig. 3. In this case, after applying the atomic physics correction, the plasma rotation measured by the views of the co- and counter-neutral beams are shown to be in agreement. This example shows a case where the atomic physics correction is especially important because the overall toroidal rotation speed is low due to co- plus counter-beam injection and magnetic braking owing to the I-coil.

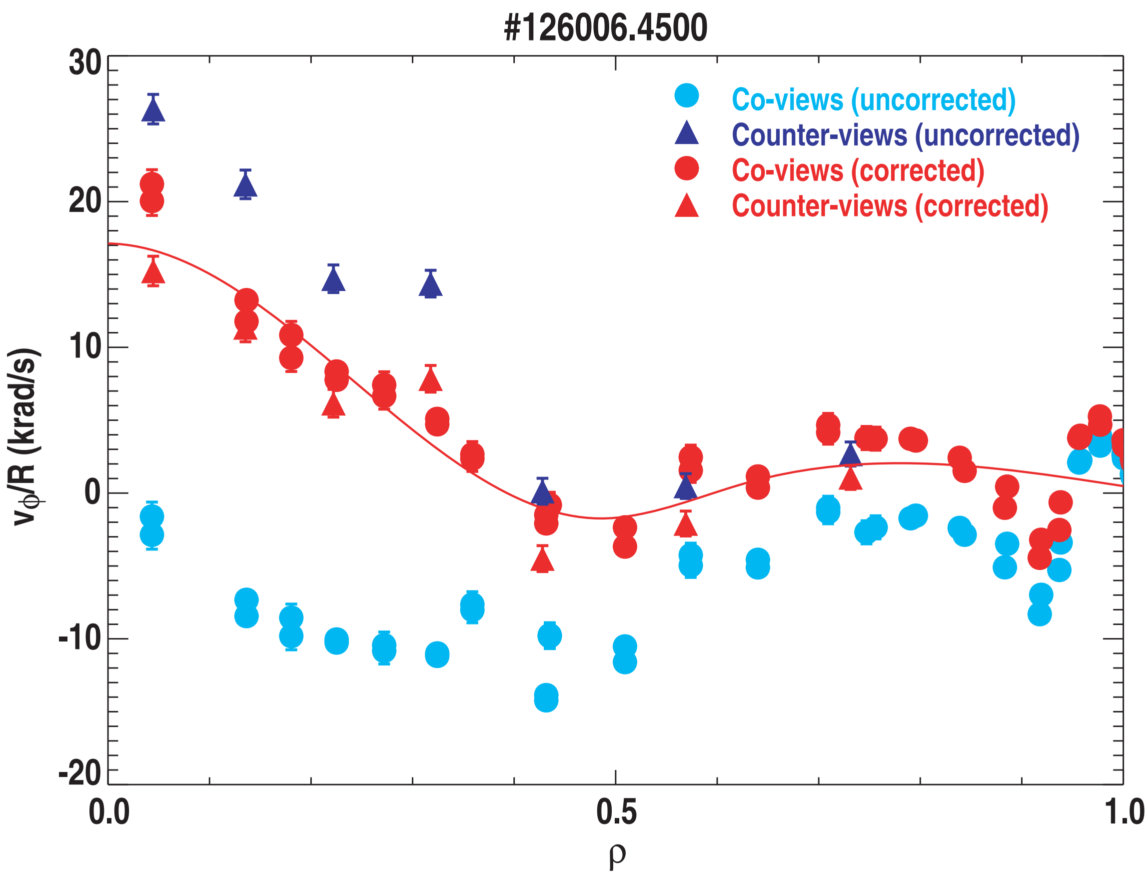

Fig. 3. Plot of angular toroidal rotation speed v_ϕ/R versus magnetic flux coordinate ρ for a case with low plasma rotation. The apparent angular rotation speed measured using the co-injected beams is plotted in cyan and while that measured using the counter injected beams is plotted in dark blue. After correction for the energy-dependent charge exchange cross section, both views (red) give the same angular rotation speed. This shot has 9.7 MW of total neutral beam power injected from a time average of four ion sources. Of these four, one tangential counter beam is used at 60% duty cycle and the remainder are co-injected beams. Non-axisymmetric n = 3 magnetic fields from the I-coil are also present at this time.

B. Resistive wall mode stabilization at low rotation

New studies of the stability of the resistive wall mode have become possible with the capability to vary the plasma rotation with co- and counter-neutral beam injection. Recent DIII-D experiments have shown that the plasma rotation threshold for stable operation above the no-wall beta limit is more than a factor of 2 lower than previously reported. Earlier experiments indicated that RWM stability typically required a minimum plasma rotation velocity, evaluated at the $q = 2$ surface, of 1% of the local Alfvén speed [3,4], consistent with theoretical modeling [5]. In those experiments with strong, uni-directional neutral beam torque, magnetic braking by intrinsic or applied magnetic perturbations was used to slow the plasma, and resonant effects of the perturbation may have led to a larger rotation threshold than required for RWM stability. In contrast, in recent experiments with low input torque and minimal non-axisymmetric field errors, stable DIII-D discharges have been observed with beta exceeding the no-wall stability limit by more than 30% and rotation velocities of less than 0.3% of the Alfvén speed at the $q = 2$ surface. In the example shown in Fig. 4, the rotation at the $q = 2$ surface remains well below 1% of the Alfvén speed (about 50 km/s) for more than 1 second. These results suggest that wall stabilization of high beta plasmas in ITER and other future devices may be possible with relatively modest rotation, given sufficiently small magnetic field errors. This discovery alone more than justifies the work needed to reverse the 210 beamline.

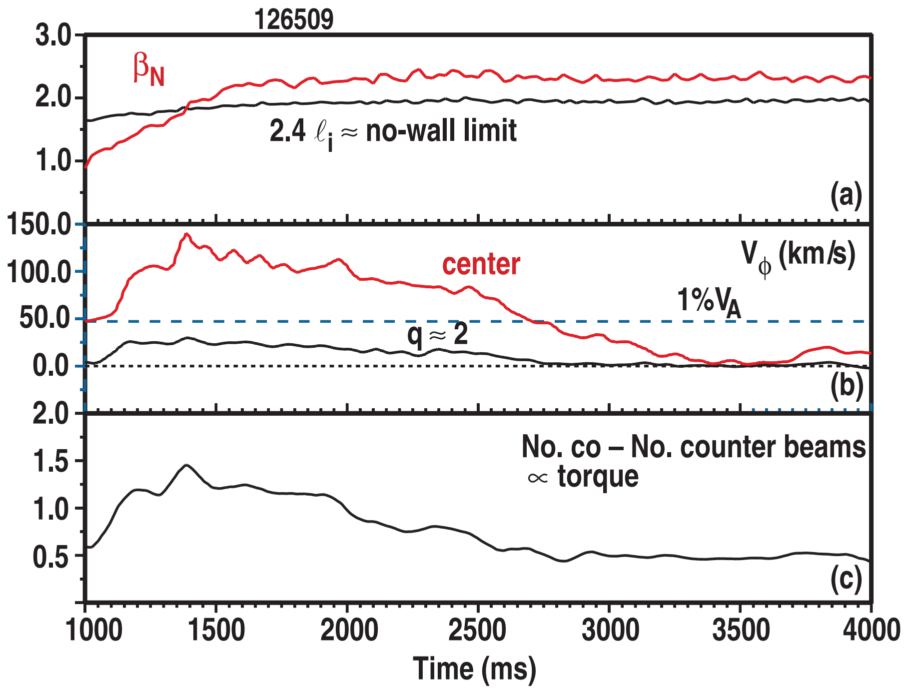

Fig. 4. Time history of a discharge showing operation 30% above the no-wall stability limit for a period exceeding 2300 ms. (a) normalized beta, β_N, and the no-wall limit for this discharge shape, (b) toroidal rotation speed at the plasma center and at the $q = 2$ surface compared to 1% of the Alfvén speed V_A, the previously determined stabilization limit, (c) co-counter beam mix used to control the plasma rotation.

C. Effect of rotation on transport in advanced tokamak plasmas

Understanding plasma rotation is an important area of tokamak research because the rotation effects on the $E \times B$ shearing rate can substantially alter plasma energy and momentum confinement. Accordingly, in order to have a predictive understanding of confinement, we need to understand plasma rotation. As part of this work, we are using the co- plus counter-neutral beam capability to study how rotation changes with input torque. One such set of experiments was performed in advanced tokamak plasmas using PCS control to keep the stored energy constant as the co-counter neutral beam mix was varied. As is illustrated in Fig. 5 this allows us to vary the plasma rotation while keeping the other plasma profiles constant. Transport analysis using the TRANSP code [6] demonstrates substantial changes in the inferred angular momentum diffusivity and the electron and ion thermal diffusivities. These changes are shown in Fig. 6. These changes in the diffusivities are probably due to the change in the $E \times B$ shearing rate although simulation and modeling calculations are needed to confirm this.

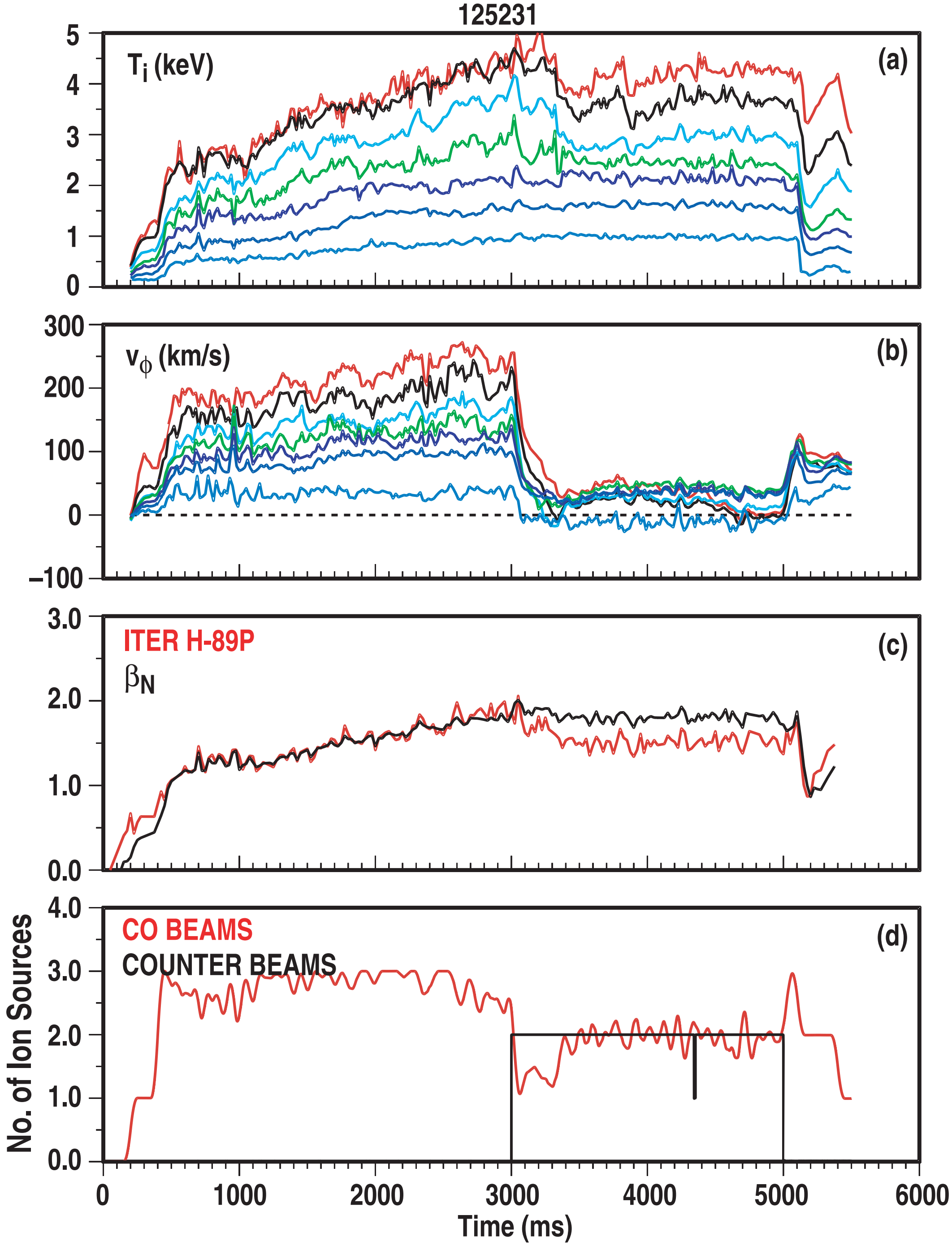

Fig. 5. Plot of ion temperature (a) and toroidal rotation speed (b) as at various radii a function of time for a shot in which the number of co- and counter-neutral beams (d) is changed at 3000 ms, altering the toroidal rotation speed. As is illustrated by the normalized beta $\left(\beta_N\right)$ trace in (c), the stored energy is feedback controlled to maintain a constant level while the co-counter beam mix is changed. This change in beam mix results in a small change in global energy confinement, as is shown by the ITER-89 H-factor in (c).

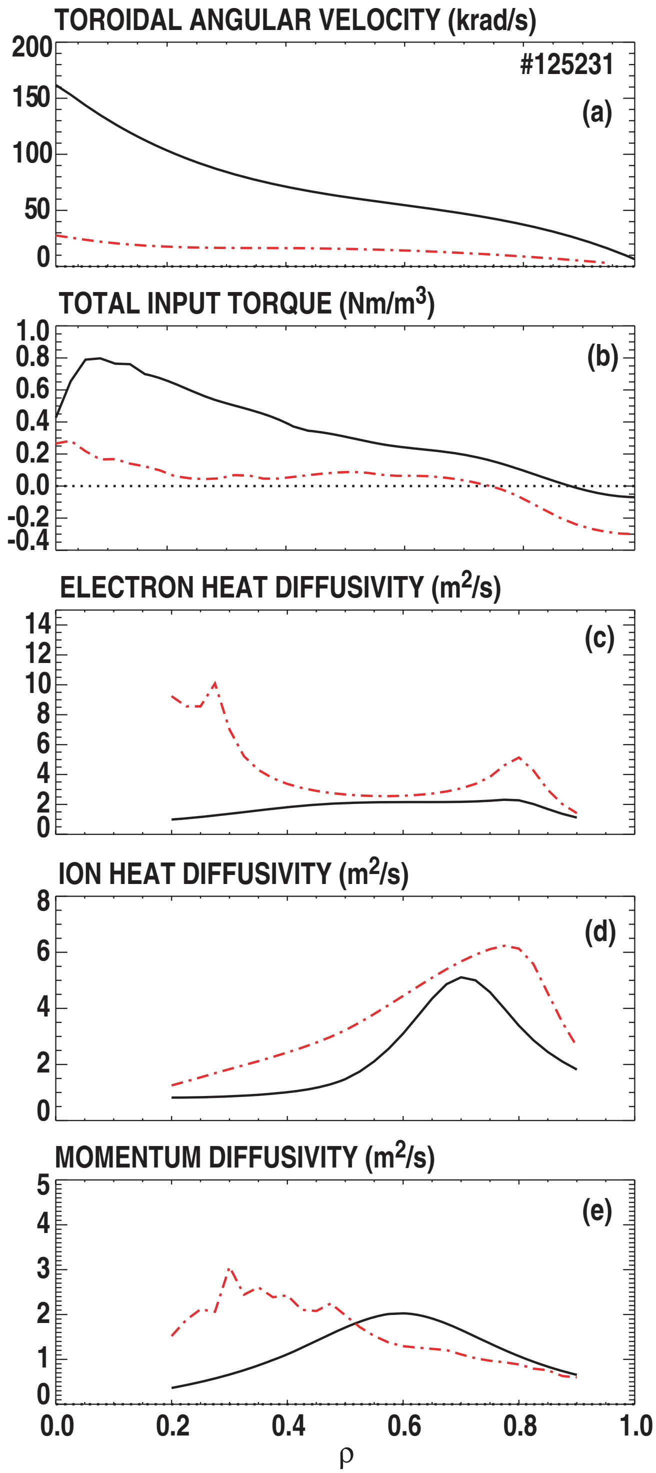

Fig. 6. Transport analysis for shot in Fig. 5 averaged over the time interval 2600-2900 ms (black curves) and 3500-3800 ms (red curves). Electron and ion thermal transport increases everywhere in the discharge for the lower rotation case while angular momentum transport increases inside of $\rho = 0.5$.

D. ITER hybrid discharges at low rotation

Experiments on the DIII-D tokamak have developed a long duration, high performance hybrid scenario that is an attractive operating mode for ITER [7]. Using the new ability to vary input power and torque separately, the properties of the hybrid scenario have been investigated in DIII-D in low rotation plasmas that have a more ITER-relevant Mach number. The principal observation is that the toroidal rotation can be reduced by up to a factor of 6, to $M_0 = 0.075$ ($M_0 =$ Mach number at the magnetic axis), while maintaining the beneficial characteristics of hybrid plasmas. Figure 7 shows the time history of a hybrid discharge with $\beta_N \simeq 2.5$ and $q_{95} = 4.6$, where a transition is made from co-injected beams to nearly balanced (co-injection plus counter-injection) beams at 3.5 s. At nearly constant β_N, the n_e, T_e, and T_i profiles do not change significantly, but the required heating power increases. The initial injected beam power and torque are 6.4 MW and 4.9 N-m, respectively. With 4.2 MW of counter-NBI beginning at 3.5 s, the total injected power rises to 9.4 MW and the input torque drops to 1.0 N-m. Figure 7 shows that another effect of reduced rotation is to increase the size of the $m/n = 3/2$ NTM island. Although the neutral beam current drive (NBCD) decreases with counter-injection (the initial co-NBCD is 20% of the total current), the sawtooth oscillation remains absent in the hybrid plasma and the overall change in the q profile is small. While the energy confinement decreases and the $m/n = 3/2$ NTM amplitude increases at low rotation, the fusion performance parameter, $G = \beta_{NH_{89P}} / q_{95^2}$, for low q_{95} plasmas still exceeds the value required on ITER for $Q_{fus} = 10$ operation. Figure 8 shows the toroidal rotation and torque density profiles before and after 3.5 s, as well as the changes in the profiles of the thermal and angular momentum diffusivities from TRANSP analysis. As the toroidal Mach number decreases, the electron and ion thermal diffusivities increase, and the momentum diffusivity also increases in the interior region. The increase in transport is likely due to the reduction in $E \times B$ flow shear, and theoretical modeling is underway to verify this. The rotation experiments have provided some unification of our understanding of the properties of hybrid plasmas as rotation, q_{95}, 3/2 NTM amplitude, and energy confinement are clearly correlated. While these observations lead to optimism about the projections of the hybrid scenario to low rotation plasmas in ITER, they also point to the need for a better understanding of toroidal momentum transport.

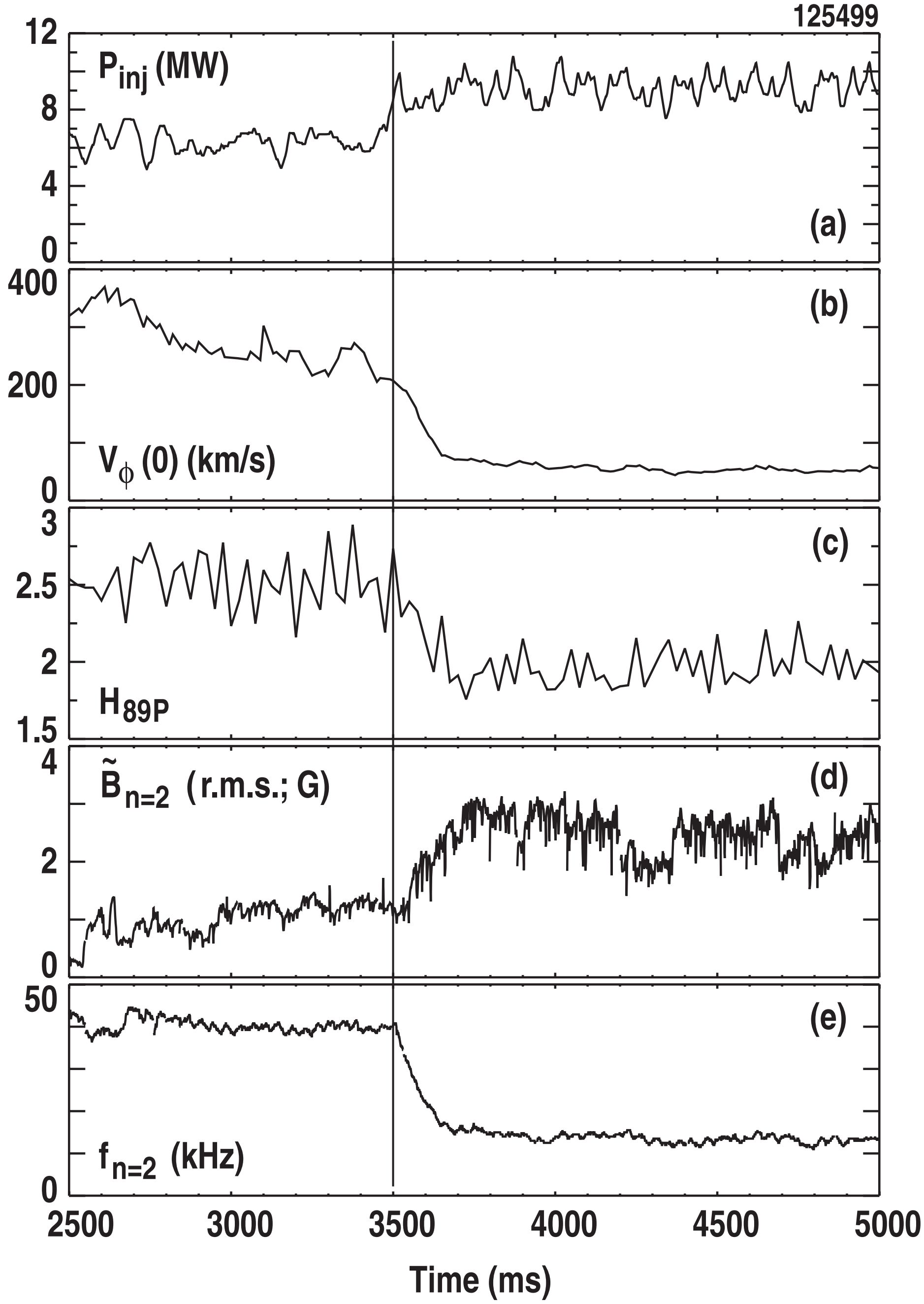

Fig. 7. Time history for a hybrid discharge in which counter-injected beams are added at 3500 ms. The stored energy is feedback controlled to remain constant; since global confinement drops as shown by the ITER H-89P value (c) as rotation drops (b), the beam power (a) increases. The amplitude of the $m/n = 3/2$ tearing mode increases as the rotation drops; this mode is a key, characteristic feature of the hybrid operating mode.

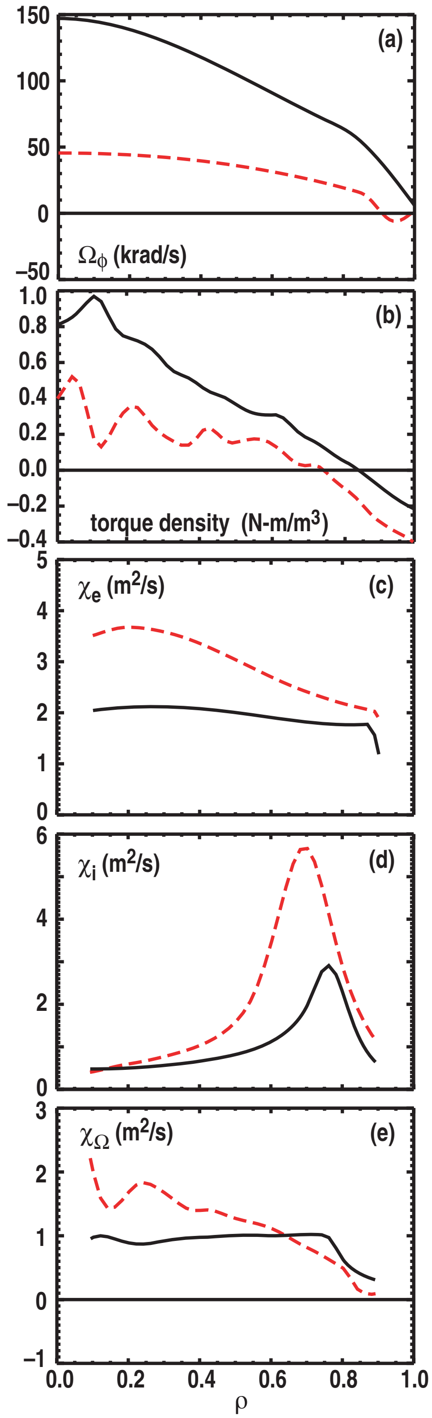

Fig. 8. Transport analysis for shot in Fig. 7 averaged over the time interval 2990-3480 ms (black curves) and 4050-5720 ms (red curves). Electron and ion thermal transport increases everywhere in the discharge for the lower rotation case while angular momentum transport increases only inside of $\rho = 0.6$.

E. Quiescent H-mode with co- plus counter-beams

Quiescent H-mode is an ELM-free H-mode capable of steady state operation. First discovered in DIII-D, QH-mode has now been seen on JET, ASDEX-Upgrade and JT-60U [8]. On DIII-D, producing QH-mode has always required counter-neutral beam injection. A key question is how much co-injection can be added to a QH-mode plasma before the QH-mode is lost. Using the new beam capability on DIII-D, we investigated this by creating QH-mode plasmas with pure counter injection and then adding various fractions of co-injection while keeping the total input power constant. (For diagnostic reasons, this was done by reversing the plasma current so that the 210 deg beamline became the co-beam.) As is shown in Fig. 9, the edge rotation drops and the edge pedestal density increases as the fraction of co-beam power is increased. When this fraction reaches about 25%, the edge density increases enough that the ELMs return. These data indicate that the edge particle transport is sensitive to the edge rotation and, accordingly, by varying the co-counter beam mix in QH-mode, we can alter the particle transport. The mechanism for this is still under investigation; we believe that the physics involves the effect of rotation on the edge harmonic oscillation, an edge MHD mode which is known to produce enhanced edge particle transport in QH-mode.

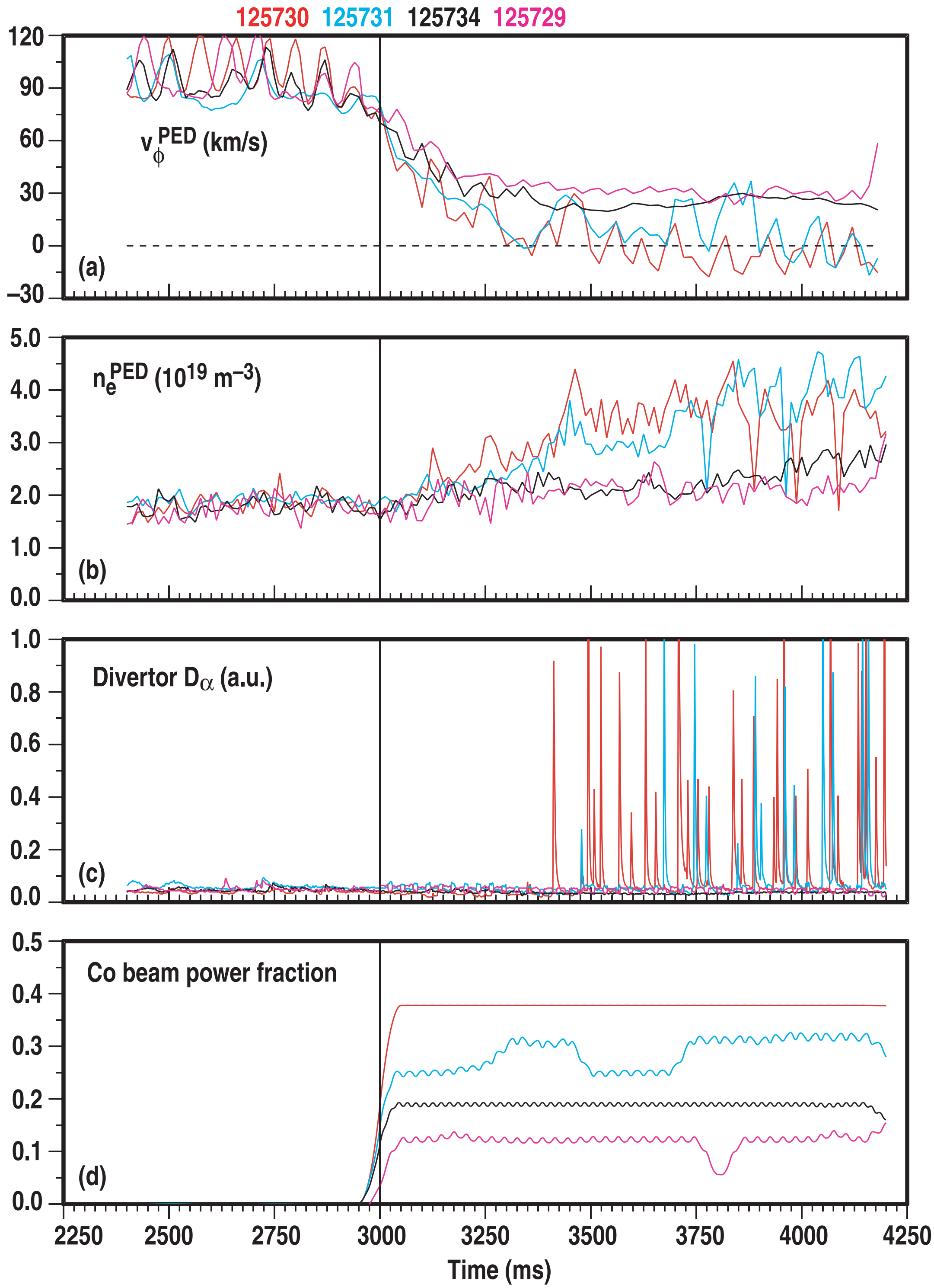

Fig. 9. Plot of QH-mode discharges with various levels of co-injected beam power after 3000 ms. As the co-injected fraction (d) increases above about 0.25, the pedestal rotation speed (a) decreases to a point where the pedestal density (b) rises above the threshold for ELMs (c) to return.

F. ELM suppression at low rotation

RMP ELM control experiments [9,10], with $n = 3$ I-coil currents ranging from 3 kA to 6.4 kA, have been done in low toroidal rotation plasmas with electron pedestal collisionalities between 0.1 and 2.0. In these plasmas the minimum in edge rotation was scanned over a range of 60 km/sec using a combination of 5 co-NBI and 2 counter-NBI sources. The level of RMP screening was characterized by measuring indirect effects such as changes in the pedestal pressure profiles and ELM behavior. These effects associated with RMP screening have significantly different signatures as the pedestal collisionality increases. At higher pedestal collisionalities the data suggests that lower poloidal mode number RMP modes penetrate better as the toroidal rotation is reduced. At present, conclusions about the behavior of the higher poloidal mode number RMP modes are less clear but there is evidence in some cases that they are also affected by the toroidal rotation as the collisionality is reduced.

G. Effect of beam direction on Alfvén eigenmodes

DIII-D experiments have also studied the dependence of Alfvén Cascade and Toroidal Alfvén Eigenmodes (TAE) on fast ion direction. NBI heating sources with the same energy were used keeping the main plasma parameters constant. The experiments used a magnetic field $B_T = 2.1\ \mathrm{T}$, plasma current $I_p = 1.1\ \mathrm{MA}$, density $10^{19}\ \mathrm{m}^{-3}$, and employed low power (~5 MW) NBI injected in the co- and counter- direction with beam voltage 81 keV. Alfvén cascades and TAEs are observed in both cases, however the number of Alfvén eigenmodes is much reduced in the case of dominant counter-beam injection, as is seen in Fig. 10. This confirms that Alfvén eigenmodes driven by passing ions--the dominant drive mechanism expected in ITER--are highly sensitive to the direction of the ion motion. The asymmetry in beam direction can be attributed to differences in the fast ion distribution owing to finite orbit width effects and to a possible intrinsic sensitivity of these modes to the direction of the particle motion.

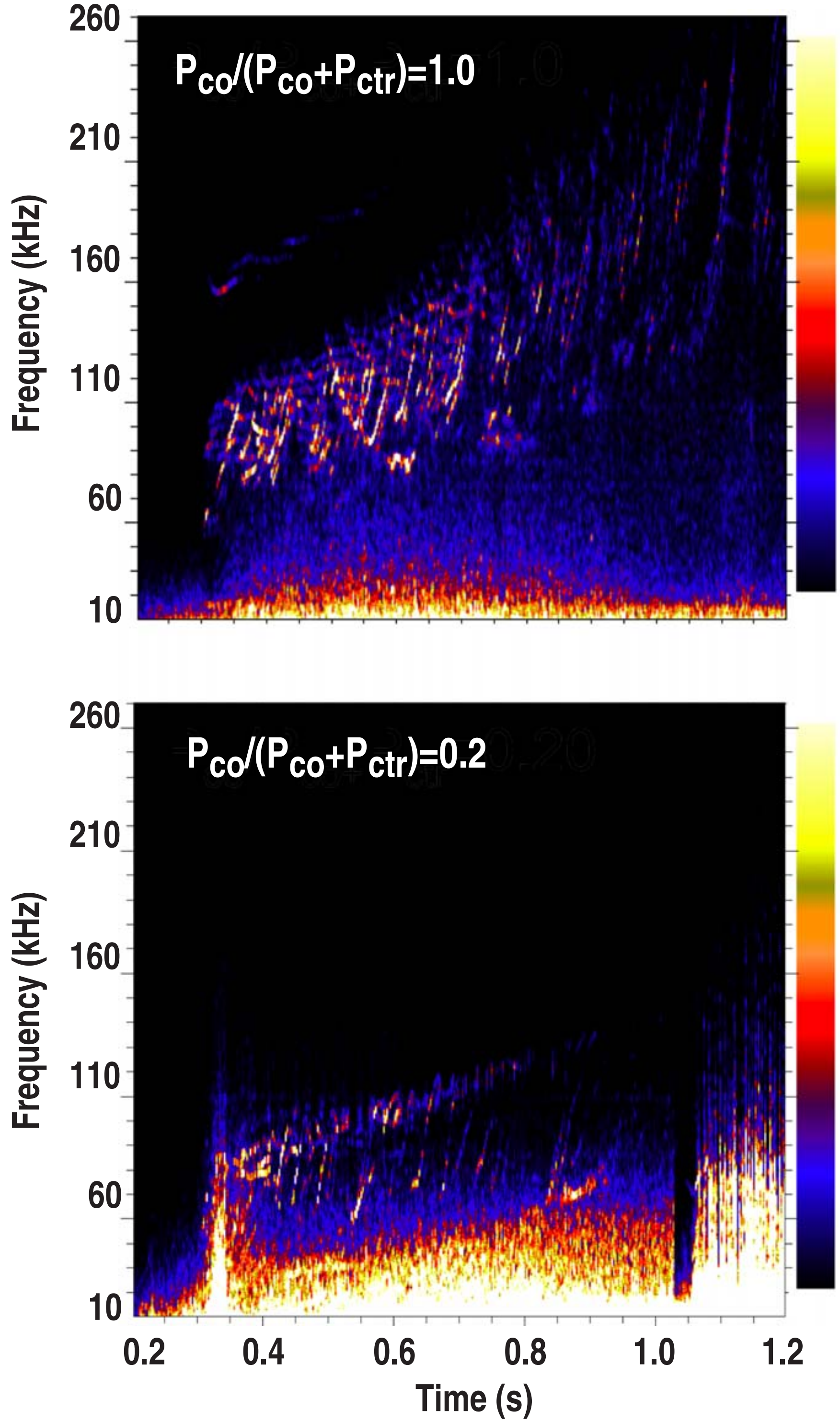

Fig. 10. CO_2 interferometer measurements of Alfvén eigenmodes in 2.1 Tesla DIII-D discharges with 5 MW of injected deuterium beams for all co-injection (top) and 20% co-injection (bottom).

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